

## How Many Hot Subdwarf Stars Were Rejected from the PG Survey?

R. A. Wade,<sup>1</sup> M. A. Stark,<sup>1</sup> and R. F. Green<sup>2</sup>

<sup>1</sup>*Pennsylvania State University, Dept. of Astronomy & Astrophysics,  
 525 Davey Lab, University Park, PA 16802, USA*

<sup>2</sup>*NOAO, P.O. Box 26732, Tucson AZ, 85726-6732, USA*

**Abstract.** It has been suggested that many hot subdwarfs lurk in the pile of rejected UV-excess candidate stars from the Palomar-Green (PG) survey. This suggestion is not supported by available photometric data.

### 1. Introduction

During the PG survey for ultraviolet excess (UVX) objects, candidate UVX objects were those with (transformed)  $U - B < -0.46$ . It was recognized that the large error in  $U - B$ ,  $\sigma \approx 0.38$ , meant that color selection should be supplemented by spectroscopy for classification, since more accurate temperature information was likely available from the spectra than from  $U - B$ . Many *candidate* UVX targets were indeed culled from the final PG catalog (Green et al. 1986: GSL86), because their classification spectra showed the Ca II K line in absorption. These K-line stars were thought not to be genuinely hot, but rather to be metal-poor subdwarf F or G stars that crept into the candidate list owing to a combination of low metal-line blanketing and photometric errors.

Hot subdwarf stars (especially sdB stars, but including some sdO stars) are understood to belong to the Extended Horizontal Branch (EHB), and as such are core-helium burning objects with very thin hydrogen envelopes. Recently, there has been renewed interest in scenarios of the origin of hot subdwarf stars that involve binary star processes (Roche-lobe overflow, common-envelope evolution) to strip the hydrogen-rich envelope away from the helium core, near the time of He-core ignition (Han et al. 2002, 2003).

In comparing their population synthesis models with observations, Han et al. (2003) drew attention to the K-line stars rejected from the PG catalog, as possibly representing a “missing” group of hot subdwarfs, hidden by their cooler and (somewhat) brighter binary companions. Owing to dilution of the hot star’s energy distribution by the companion, the  $U - B$  color could be marginal for the PG color criterion, while the cool star would contribute a K line, much as a metal-poor subdwarf would show. In this interpretation, therefore, these “PG-rejects” actually belong in the PG catalog, and moreover would constitute important evidence in favor of binary formation channels for sdB.

Han et al. have put forward a hypothesis that can be tested. The list of PG-rejects exists in a card file (with finding charts) kept by RFG. Here we report our investigation to date of the PG-rejects.

## 2. The Sample of Rejected K-line Stars

We have assembled a catalog of 1125 distinct PG-rejects. We found 291 stars that are present in both the Two-Micron All-Sky Survey (2MASS) Point Source Catalog and the Sloan Digital Sky Survey (SDSS) DR2 survey region. Here we focus on the 173 stars with Sloan  $r$  magnitudes in the range 14.00 to 16.00 (median  $r = 14.86$ ). Of these, 136 have all 5 optical magnitudes ( $ugriz$ ), and all were measured in the 2MASS  $J$ ,  $H$ , and  $K_s$  bands.

Many K-line stars were observed spectroscopically *before* the final  $U - B$  transformation (from photographic to Johnson  $U - B$ ) was established. In the subsample of 291 stars, only 150 would have met the final  $U - B$  criterion for inclusion in the PG catalog, while 131 have final  $U - B$  colors redder than the catalog cutoff and 10 were from survey fields not included in the final catalog.

Figure 1 shows aspects of the SDSS/2MASS photometry for the 173 K-line stars (rejected from the PG catalog), along with data for 199 PG stars classified as hot subdwarfs. Not all of the objects for which SDSS/2MASS photometry is available are shown in each diagram, i.e., sometimes the needed color cannot be computed. Also shown in the Figure are loci for the main sequence (solar abundance), metal-poor main sequence, and metal poor giants representing horizontal branch stars.

Three sequences of composite (binary) models are also shown. These represent the light from a hot subdwarf star ( $T_{\text{eff}} = 25000$  K, 30000 K, and 35000 K, with  $M_V$  derived from the zero-age EHB calculations of Caloi 1972), combined with the light from a cool main-sequence companion (eight  $T_{\text{eff}}$ 's ranging from 4000 K to 9750 K). These sequences emerge from the hot end of the stellar locus (faintest, coolest companions at this end), loop away from the single-star locus, and then loop back to meet the stellar locus at a (single-star)  $T_{\text{eff}}$  near 10000 K.

The recognized PG hot subdwarfs and the K-line PG-rejects are very different groups of stars. In this sense, the classification spectroscopy carried out by GSL86 was successful in improving on the photographic  $U - B$  color selection. It is also clear that some PG subdwarfs are composite objects (a conclusion already reached by Stark & Wade 2003; see also Reed & Stiening 2004, and poster by Stark & Wade at this conference). Finally and most important, *the PG-reject stars are consistent with being single stars*, possibly metal poor, just as they were interpreted to be by GSL86. Except for a few outliers, *they are not binaries composed of a ZAEHB subdwarf and a main-sequence companion*.

## 3. Fitting the PG-reject Stars as Single Stars

We compared the observed magnitudes for the 173 stars with model magnitudes, derived from the synthetic photometry done by the Padova group (Girardi et al. 2002, 2004) using Kurucz stellar atmosphere energy distributions. As single-star models for the PG-reject stars, we considered all available Padova models with  $T_{\text{eff}}$  in the range 4000 – 50000 K ( $\log g = 4.0, 4.5, 5.0$ ), with metallicities  $[M/H] = 0.0, -1.0, -1.5, -2.0, -2.5$ . We interpolated in  $T_{\text{eff}}$  to make the grid denser.

For each of the 173 stars, we scaled each model in brightness to find the best fit. We chose as the best overall model, that model that gave the smallest

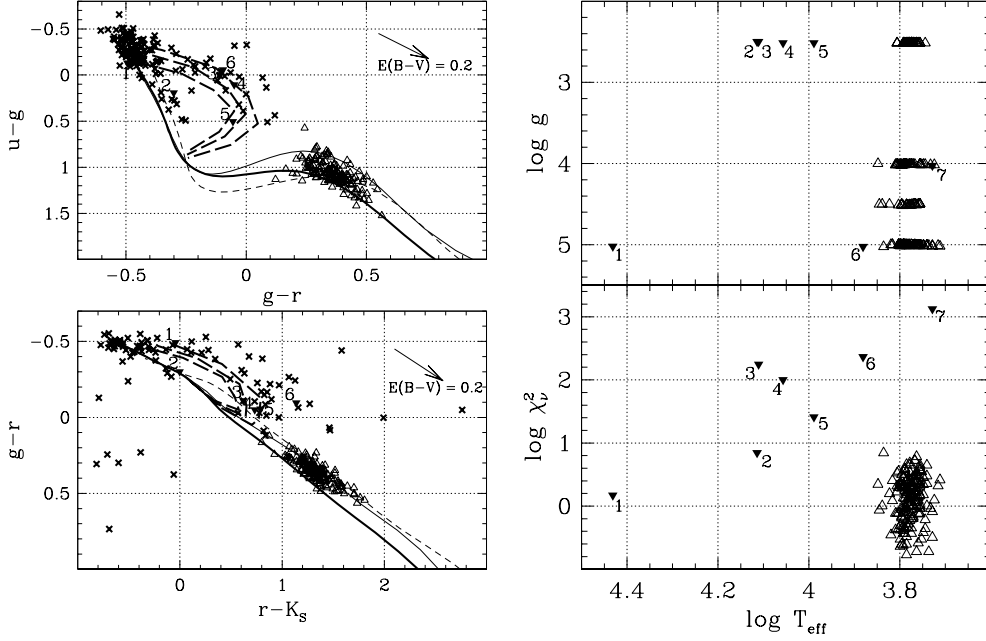


Figure 1. *Left panels:* Color-color diagrams of hot subdwarfs from the PG catalog (crosses) and K-line “PG-reject” stars (triangles). Errors on  $K_s$  are sometimes large for the PG subdwarfs, contributing to the apparent scatter in the lower panel. Heavy black line – main sequence locus,  $\log g = 4.5$ , solar metallicity  $[M/H]=0.0$ ; thin black line – metal-poor main-sequence locus,  $\log g = 4.5$ ,  $[M/H]=-1.5$ ; thin dashes line, metal-poor giant locus,  $\log g = 2.5$ ,  $[M/H]=-1.5$ . heavy dashes – composite colors for hot subdwarf + main sequence binaries. *Right panels:* Results of fitting single-star models to the SDSS/2MASS photometry of PG-reject stars. Seven objects are clear outliers either in temperature or in the quality of the fit (filled triangles), while 166 stars have satisfactory fits and are tightly clustered (open triangles). *Upper:*  $T_{\text{eff}}$  and  $\log g$ . Objects shown at low  $\log g$  may have fits at higher  $\log g$  that are only slightly worse. Stars with lower metallicity  $[M/H]$  are plotted with a slight offset downward; otherwise  $\log g$  has only four discrete values. *Lower:*  $\chi^2_\nu$  is satisfactory (smaller than  $\sim 10$ ) for 166 stars. Median value is  $\chi^2_\nu = 1.49$ . Further improvement is possible by using additional values of  $[M/H]$  and  $\log g$ , plus interstellar reddening.

reduced chi-square statistic,  $\chi^2_\nu = \chi^2/\text{dof}$ , where  $\text{dof} = 6$  (or 7) is the number of degrees of freedom for 7 (or 8) valid magnitudes.

The main results are summarized in Figure 1 (right-hand panels). Seven outliers have either large  $\chi^2_\nu$  or unusual  $T_{\text{eff}}$  or  $\log g$ . All of the remaining 166 PG-rejects are fitted with  $T_{\text{eff}}$  in the range 5000 – 7100 K. Most of the stars (136 of 166) are preferably fitted with low-metallicity models,  $[M/H] = -1.0$  or below. These are *consistent with the GSL86 interpretation that these are metal-poor F and G subdwarfs*. The locus for low-gravity models in Figure 1 also passes through the cluster of PG-reject stars, so sometimes the absolute

best-fitting model by the  $\chi^2$  criterion is a low-gravity model (39 cases out of 166); models nearly as good will likely be found at higher  $\log g$ .

Given our present understanding of the systematics of the SDSS error estimates and the incompleteness of our model grid, the  $\chi^2_\nu$  values for the 166 non-outliers are acceptably small. A trend in  $T_{\text{eff}}$  with  $r$  magnitude indicates that reddening may need to be taken into account for the fainter (more distant) stars; when this is done, the  $\chi^2_\nu$  values may decrease further.

Some outliers are identified by numbers in Figure 1. Two of the outliers have SDSS spectra. Star #2 may be a blue horizontal branch star. Star #3 appears not only in the PG-reject list, but also in the PG catalog itself (PG 1723+603)! The spectrum shows Mg Ib, Na D, and Ca II infrared triplet absorption, but the continuum is blue. In Figure 1, it lies in the region of the composite models. Star #5 also lies in the region of the composite models in Figure 1 with similar but weaker evidence of ‘cool’ stellar features such as Mg Ib and Na D. The spectral energy distribution of Star #7 shows ‘excesses’ at both the short and long-wavelength ends relative to the (not-so-good) best-fitting single-star model, suggesting that it is composite. The other outliers lie either close to the hot single-star locus or close to the sequences of composite models.

#### 4. Summary

A very few objects in our sample of PG-reject stars may plausibly be binary systems with a hot subdwarf star component. Also, a few objects seem to have entered the PG-reject list by accident. The vast majority of the PG-reject stars, however, are sufficiently modeled as single stars consistent with their being the metal-poor sdF/sdG contaminants that GSL86 were guarding against. The color-color sequences of sdB + cool star binaries (with  $M_V$  for main sequence companions!) are well separated from the observed colors of the PG-reject stars. There is at present no compelling evidence for large numbers of additional hot subdwarf stars hiding in binaries that were rejected from the PG catalog.

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